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TITLE: Body Heat Storage and Work in the Heat

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13. ABSTRACT (Maximum 200 Words)

The initial period (FY02) was spent preparing supporting information for the award, gathering the parts and supplies for the construction of the two calorimetry systems, convening of a kickoff meeting for the project, and restructuring of the proposal to allow University of Ottawa to assume responsibility as the primary Performing Organization. In FY03, a Cooperative Research and Development Agreement was developed and signed between NHRC and Univ. of Ottawa to allow reciprocal support between this MIPR and contract DAMD 17-02-2-0063 at the Univ. of Ottawa, a calibration manikin for the calorimetry systems was constructed and provided to Univ. of Ottawa, and the liquid-cooled garment calorimeter was rebuilt at NHRC.

14. SUBJECT TERMS

Exercise, heat, human thermal response, heat storage, body heat content, calorimeter, liquid-cooled garments, air calorimeter, indirect calorimetry, open-circuit spirometry, muscle temperature

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INTRODUCTION:

The development of heat injury during military ground operations in hot environments is a serious risk, particularly when operations in chemical defense ensembles are required. The objective of the research is to develop a model of body heat storage from readily available field and clinical measures that can be used to predict response to work in the heat, with or without the inclusion of impermeable or semi-impermeable garments. Unique aspects of these models will be the use of a three-compartment approach, in which muscle-mass temperature will be measured in addition to skin and non-muscle core temperature values, and measurement of heat storage by direct and indirect calorimetry.

Proposed is a series of studies to investigate improvements to heat storage calculation during exercise and exercise in the heat that is provided by measurement of muscle temperature during exercise and exercise in the heat. Three studies will be carried out under this work unit. The first of these will be cross calibration of the tube-suit direct calorimeter with the Snellen air calorimeter. The second study will consist of development a model for body heat storage during exercise. Heat storage will be calculated from direct and indirect calorimetry during exercise. This second study will utilize the tube suit as the direct calorimeter. The third study will extend the model development to exercise in hot ambient conditions and will utilize the air calorimeter, rather than the tube suit.

BODY:

Accomplishments

<u>FY02</u>: Supporting documentation from all the institutions involved in the project was collected and provided to the project sponsors.

Funding was received 12 May 2002.

Parts for the liquid-cooled garment (LCG) calorimetry system were located, plans for system repair were developed, and rebuilding of the system was begun.

Parts for the air calorimeter were located at the University of Ottawa, and a space was identified to house the calorimeter.

A kickoff meeting was held at the University of Ottawa in July 2002. Plans for the construction of the air calorimeter were reviewed and refined.

It was determined in July 2002 that a suitable mechanism for continuing the funds for this project at the Naval Health Research Center (NHRC) beyond FY2002 could not be found. It was decided to restructure the project with University of Ottawa becoming the primary Performing Organization. Approval was obtained from USAMRAA to pursue this approach. NHRC returned $890,516.30 of the original award of $1,117,448.00 to USAMRAA, holding $226,931.70 to cover first year costs, and anticipated supplies, equipment and travel for NHRC for the remainder of the project.

<u>FY03</u>: A Cooperative Research and Development Agreement (CRADA) between the University of Ottawa and NHRC was negotiated (NCRADA-NHRC-03-1523, signed 28 March 2003). A calibration manikin for the calorimetry systems was constructed. The LCG calorimeter was rebuilt at NHRC. Two planning meetings were held at the University of Ottawa.

The CRADA was developed to allow NHRC participation in and cooperation with the "Body

Heat Storage and Work in the Heat program, which had been transferred to the University of Ottawa for administration (DAMD 17-02-2-0063). NHRC had withheld funds from the original MIPR associated with this project. The funds were retained at NHRC in ongoing contracts to support the purchase of equipment, materials, travel and contract labor associated with the project. Under the CRADA, University of Ottawa agreed to pay federal salaries and support other contract salaries associated with the project.

NHRC Institutional Review Board (IRB) conducted a review of the Canadian research protocol and did not approve the protocol, primarily due to concerns with the level of language in the Informed Consent Document (ICD). Because the protocol was also under review at USAMRMC, the NHRC suggestions were not incorporated into the Univ. of Ottawa ICD.

Construction of the liquid-cooled garment calorimeter system was completed. The system underwent engineering tests (accuracy of the flow and temperature measurement and control systems), and passed them.

FY04: The first human test of the LCG resulted in a broken water line on the calorimeter. However, the trial did indicate that the system was capable of measuring heat storage during exercise. Metabolic rate increased immediately with the start of exercise, but the heat extraction by the suit remained at essentially resting levels for about 20 minutes, and then began to rise prior to the water line rupture. The plumbing problems have been fixed, but no further tests have been conducted.

The calibration manikin was shipped to Univ. of Ottawa to support testing and calibration of the air calorimeter.

A research meeting was held at the Univ. of Ottawa in December 2003. At this meeting, it was decided that all of the research would be conducted at the Univ. of Ottawa. This decision was reached because (1) the lack of NHRC approval of the Univ. of Ottawa protocol made NHRC participation in the project problematic, and (2) the grant, as restructured, had insufficient funds to allow the procurement of the needed level of surgical support for conduct of the research at NHRC. That support was already in place at the Univ. of Ottawa.

An attempt was made to restructure a CRADA with the Univ. of Ottawa. Agreement could not be reached. The University was unwilling to provide any further support for federal salaries at NHRC. Therefore any further work by NHRC civilian staff on this project would violate Navy regulations. At this point, there appears to be no further interest in the LCG calorimeter without extensive testing of the system, and there is no provision of any further support for such testing.

For the remainder of the Fiscal Year, we will carry out testing of the LCG calorimeter under a separate NHRC work unit dealing with evaluation of cooling devices. We have purchased a second calibration manikin (the first having been delivered to Univ. of Ottawa) with the remaining funds for which we will acquire the supporting equipment. A final report will be issued upon completion of the LCG tests.

A listing of expenditures funded by this MIPR and contributions from Univ. of Ottawa under the CRADA is provided in Appendix A.

KEY RESEARCH ACCOMPLISHMENTS:

- A calibration manikin was developed, constructed and shipped to the University of Ottawa. This manikin was instrumental in calibrating and allowing the development of other indirect calibration techniques for the air calorimeter temperature and humidity measurement systems.
- Rebuilding of the LCG calorimeter was completed. We now have a LCG calorimeter capable of measuring heat exchange in six body regions. A description of the calorimeter is provided as Appendix B. With the acquisition of a second calibration manikin, testing of the suit capabilities will be carried out under a separate work unit.

REPORTABLE OUTCOMES:

- None.

CONCLUSIONS:

The conduct of this research depended on cooperative agreements between NHRC and the Univ. of Ottawa. One of the goals of that agreement was met – development and delivery of a calibration manikin. Another goal, construction of the LCG calorimeter was completed, but sufficient human testing was not carried out to satisfy the Univ. of Ottawa that it would be able to make the needed measurements. A suitable cooperative agreement to complete the research could not be developed.

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APPENDIX A: HEAT STORAGE PROJECT ACCOUNTING

Naval Health Research Center - Account: Heat Storage Project

Transactions			DAMD 17-02-2-0063				MIPR 2DCJWP2055			
Type	Date	Item	Number	Item Cost	Amount	Account Value	Number	Item Cost	Amount	Account Value
Receipt	21-May-02	Award from USMRAA				$0.00	1	$1,117,448.00	$1,117,448.00	$1,117,448.00
Expense	1-Jun-02	Consultant Contract (Webb)				$0.00	1	($36,000.00)	($36,000.00)	$1,081,448.00
Expense	16-Aug-02	Travel - Webb to Ottawa				$0.00	1	($1,124.70)	($1,124.70)	$1,080,323.30
Expense	1-Sep-02	Return Award to USAMRAA				$0.00	1	($890,516.30)	($890,516.30)	$189,807.00
Expense	5-Sep-02	Travel - Webb to CA				$0.00	1	($314.00)	($314.00)	$189,493.00
Expense	5-Sep-02	National Instruments (LabView)				$0.00	1	($2,376.62)	($2,376.62)	$187,116.38
Expense	5-Sep-02	CDF (Office 2000 software)				$0.00	1	($355.00)	($355.00)	$186,761.38
Expense	30-Sep-02	Labor - Hodgdon (15% salary & fringe)				$0.00	270	($69.63)	($18,800.10)	$167,961.28
Expense	30-Sep-02	NHRC Overhead - Hodgdon (15%)				$0.00	270	($16.40)	($4,428.00)	$163,533.28
Expense	30-Sep-02	Labor - Contractor (Lab Assistance)				$0.00	285	($22.00)	($6,270.00)	$157,263.28
Expense	30-Sep-02	Contractor Overhead (Lab Assistance)				$0.00	285	($19.58)	($5,580.30)	$151,682.98
Expense	30-Sep-02	NHRC Overhead (Lab Assistance)				$0.00	285	($16.40)	($4,674.00)	$147,008.98
Expense	30-Sep-02	Labor - Contractor (Contract Management)				$0.00	285	($22.61)	($6,443.85)	$140,565.13
Expense	30-Sep-02	Contractor Overhead (Contract Management)				$0.00	285	($20.35)	($5,799.47)	$134,765.67
Expense	30-Sep-02	NHRC Overhead (Contract Management)				$0.00	285	($16.40)	($4,674.00)	$130,091.67
Expense	30-Sep-02	Labor - Contractor (Calorimeter Assistance)				$0.00	285	($33.13)	($9,442.05)	$120,649.62
Expense	30-Sep-02	Contractor Overhead (Calorimeter Assistance)				$0.00	285	($28.82)	($8,214.58)	$112,435.03
Expense	30-Sep-02	NHRC Overhead (Caloimeter Assistance)				$0.00	285	($16.40)	($4,674.00)	$107,761.03
Expense	30-Sep-02	SPAWAR contracting fees				$0.00	1	($3,478.00)	($3,478.00)	$104,283.03
Expense	17-Oct-02	Travel - Hodgdon to Ottawa				$0.00	1	($1,186.66)	($1,186.66)	$103,096.37
Expense	28-Oct-02	Computer				$0.00	1	($1,208.00)	($1,208.00)	$101,888.37
Expense	27-Nov-02	National Instruments (PCI GPIB board and cable)				$0.00	1	($1,673.25)	($1,673.25)	$100,215.12
Expense	1-Apr-03	Consultant Contract (Webb)				$0.00	1	($36,000.00)	($36,000.00)	$64,215.12
Receipt	30-Jun-03	Pmt CRADA Invoice	1	$78,119.93	$78,119.93	$78,119.93				$64,215.12
Expense	20-Aug-03	SPAWAR contracting fees				$78,119.93	1	($1,314.00)	($1,314.00)	$62,901.12
Expense	9-Sep-03	IMO industries (flow switches)				$78,119.93	1	($371.09)	($371.09)	$62,530.03
Expense	26-Sep-03	Omega Engineering (Thermocouples)				$78,119.93	1	($254.34)	($254.34)	$62,275.69
Expense	30-Sep-03	Labor - Hodgdon (10% salary & fringe)	180	($72.76)	($13,096.80)	$65,023.13				$62,275.69
Expense	30-Sep-03	NHRC Overhead - Hodgdon (10%)	180	($14.28)	($2,570.40)	$62,452.73				$62,275.69
Expense	30-Sep-03	Labor - Contractor (Calorimeter Assistance)	784	($34.41)	($26,977.85)	$35,474.88	116	($34.41)	($3,991.62)	$58,284.07
Expense	30-Sep-03	Contractor Overhead (Calorimeter Assistance)	784	($30.97)	($24,280.07)	$11,194.81	116	($30.97)	($3,592.46)	$54,691.61

Transactions			DAMD 17-02-2-0063				MIPR 2DCJWP2055			
Type	Date	Item	Number	Item Cost	Amount	Account Value	Number	Item Cost	Amount	Account Value
Expense	30-Sep-03	NHRC Overhead (Calorimeter Assistance)	784	($14.28)	($11,195.52)	($0.71)	116	($14.28)	($1,656.48)	$53,035.13
Expense	30-Sep-03	Labor - Contractor (Contract Manager)					190	($22.61)	($4,295.90)	$48,739.23
Expense	30-Sep-03	Contractor Overhead (Contract Manager)					190	($20.35)	($3,866.31)	$44,872.92
Expense	30-Sep-03	NHRC Overhead (Contract Manager)					190	($14.28)	($2,713.20)	$42,159.72
Expense	30-Sep-03	Labor - Contractor (Lab Manager)					190	($18.00)	($3,420.00)	$38,739.72
Expense	30-Sep-03	Contractor Overhead (Lab Manager)					190	($16.20)	($3,078.00)	$35,661.72
Expense	30-Sep-03	NHRC Overhead (Lab Manager)					190	($14.28)	($2,713.20)	$32,948.52
Expense	8-Oct-03	ISE (Variac)					1	($273.81)	($273.81)	$32,674.71
Expense	8-Oct-03	Vahalla Scientific (Watt Meter)					1	($1,095.00)	($1,095.00)	$31,579.71
Expense	30-Oct-03	Lowe's (Connector Wires, plugs)					1	($59.50)	($59.50)	$31,520.21
Expense	20-Nov-03	Flow Technologies (flow meter repair/calibration)					1	($4,180.00)	($4,180.00)	$27,340.21
Expense	20-Nov-03	Calibration Mannikin					1	($1,356.55)	($1,356.55)	$25,983.66
Expense	20-Nov-03	Travel - Webb to Ottawa (Nov mtg)					1	($2,334.45)	($2,334.45)	$23,649.21
Expense	20-Nov-03	Travel - Webb to Ottawa (Dec mtg)					1	($2,334.45)	($2,334.45)	$21,314.76
Expense	20-Nov-03	Consultant, Calorimeter					250	($55.00)	($13,750.00)	$7,564.76
Expense	20-Nov-03	Ship Calibration Dummy to Ottawa					1	($729.28)	($729.28)	$6,835.48
Expense	20-Nov-03	Travel - Hodgdon to Ottawa (Dec mtg)					1	($2,110.00)	($2,110.00)	$4,725.48
Expense	20-Nov-03	Construction of crates for shipping calorimeter					1	($477.00)	($477.00)	$4,248.48
Expense	30-Apr-04	Consultant, Calorimeter					30	($55.00)	($1,650.00)	$2,598.48
Expense	17-Jun-04	Calibration Mannikin					1	($2.400.00)	($2,400.00)	$198.00
Planned	8-Oct-03	ISE (Variac)					1	($273.81)	($273.81)	($75.81)
Planned	8-Oct-03	Vahalla Scientific (Watt Meter)					1	($1,095.00)	($1,095.00)	($1,170.81)

APPENDIX B: LIQUID-COOLED GARMENT CALORIMETRY SYSTEM

The Liquid-cooled Garment (LCG) calorimetry system provides a means of measuring heat produced by the body during rest and exercise. The system consists of a nylon mesh garment with water-filled plastic tubes running through it, subsystems to control the temperature and flow rate of the water in the tubes, and a subsystem for measurement of the fluid flow rate and fluid temperatures at the inlets and outlets for the suit. Water flowing through the tubes in the suit contacts the skin. Heat is gained or lost from the water depending on the water temperature, the skin temperature, and the temperature of the remaining environment surrounding the tubes (i.e. the suit itself, and the air temperature surrounding the suit). Heat loss or gain to the circulating fluid is calculated from measurements of water temperature at the suit inlet and the suit outlet, from which the temperature difference (positive or negative) across the suit is calculated, and the mass water flow through the suit. To prevent heat exchange with the environment, the person being measured is clothed in an insulated, impermeable over garment or garments. For this LCG, heat exchange is measured for six separate body regions: the head and neck, both arms, the upper torso (chest, front and back), the lower torso (abdomen and lower back), both thighs, and both legs (calf to ankle). Water flow and heat for each of these regions can be controlled independently, allowing a wide variety of heating and cooling profiles for the body.

1. System components

The LCG calorimeter components consist of a heat exchanger (the garment), a control system for water temperature and flow, a water temperature and flow measurement system, and data processing system. A diagram of the calorimeter system is provided in Figure 1. In this figure, blue lines represent water flow, and green lines indicate information flow. There is a single water chiller and circulation pump unit that provides baseline cooling for the water and pressure for the water circulation system. The water flow is then divided among six branches, one serving each of the LCG regions.

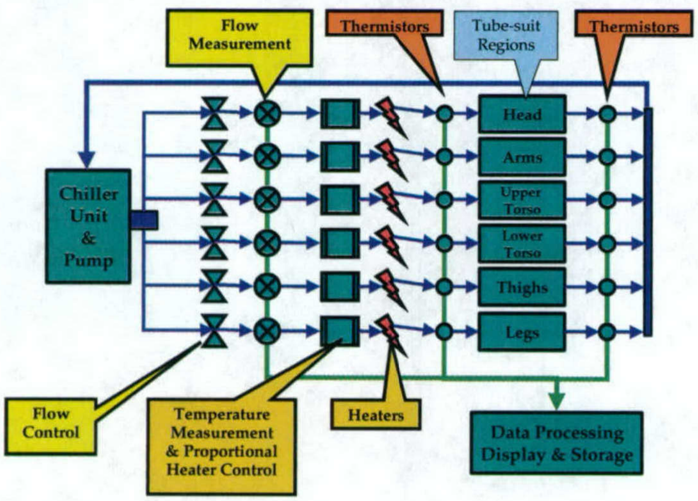

Figure 1. Diagram of LCG calorimeter system

The temperature of the chiller control is set 2-3 °C below the desired circulating water temperature. Separate heaters with proportional control units provide control of water temperature is in each of the regional circulation systems. The result is that the temperature can be varied independently for each region of the LCG. In addition, each of the six regional circulation systems has its own water flow control valve, so that perfusion can be varied by region. Independent control of water temperature and flow allows the temperature and flow to be varied to maximize the ability to measure heat extracted from regions having different metabolic heat production. In addition, this capability allows studies of complex control of body heat status by providing heat to some regions while

extracting heat from others.

Figure 2 provides a picture of the system rack, LCG and data analysis and display computer. The system rack contains the flow and temperature controls for each LCG region, the flow meters for measuring flow in each region and the data acquisition multimeters.

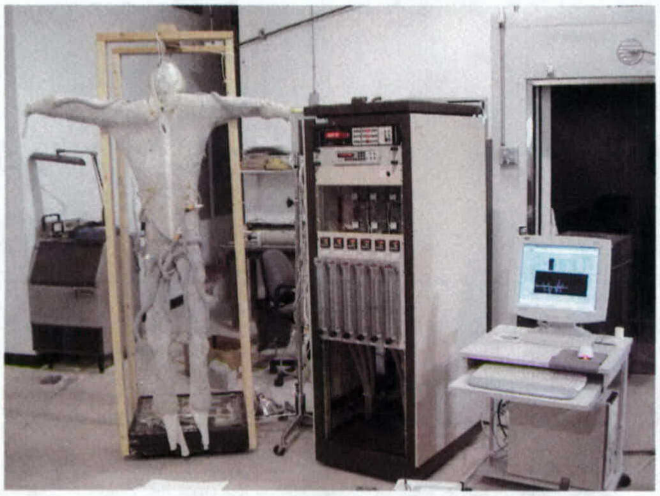

Figure 2. LCG (left), system rack (center), and computer (right).

A picture of the chiller and pump unit (Neslab™, model HX-100) for the calorimeter is shown in Figure 3. The base water temperature is set using the controls on the front of the chiller. System water pressure is controlled by the extent to which a valve on side of the chiller unit is opened.

Flow control for the LCG regions are provided manual adjustment of Dwyer™ 0 – 1.0 L•min^{-1} flow controllers mounted on a front panel on the system rack (Figure 4.)

Figure 3. Chiller/circulation pump unit

Final water temperature for each region is set manually using proportional heater controls (Love Controls Division, Dwyer Industries, Model 16020 PID) controlling 500W heaters (Omega™ TMW-1051/120) located in the six regional flow paths. Each of the proportional control units activates a solid-state relay that controls current flow to the heater. A safety flow switch (Gems™ model 26939) is wired into the circuit of each of the heaters to prevent power to the heater element when there is no water flow. Figure 5 shows the proportional controls located above the flow controls on the system rack front panel.

Figure 5. Flow control units.

Figure 4. Proportional control units for the in-line water heaters

Water flow measurement in each of the regions is measured precisely using Flow Technology flow meters (model FTO-JNINW-LHC-1 turbines, RC51-1-C-000-1 signal conditioner, and FTV0019 flow rate converter). The flow measuring turbines run on jeweled

bearings and provide electrical pulse output that is converted to an analog voltage by the signal conditioner and flow rate converter amplifier. Flow meter analog voltage outputs are connected to a digital multimeter (PREMA, model 6047). The flow signal is digitized by the multimeter and is sent to the system computer using a General-purpose Interface Buss (GPIB, IEEE-488) with the system computer as the controller.

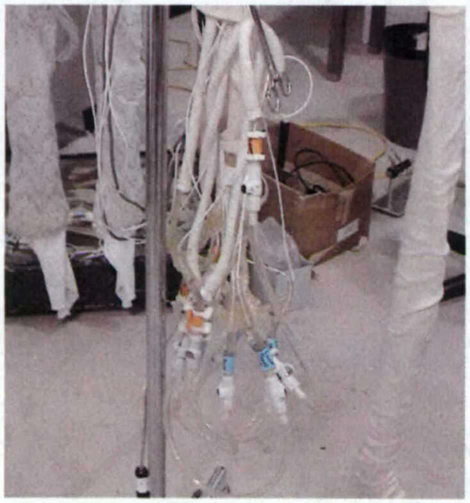

Figure 6. Umbilicus for transfer of water to and from the water conditioning system. Thermistors are housed in one arm of the "Y" tubes joined to the tubing connectors.

Water is provided to the LCG through an umbilicus containing six insulated water supply tubes and six insulated water return tubes. Inlet and outlet water temperatures are measured at the end of the umbilicus adjacent to the suit connections using precision, glass-coated, stabilized thermistors (Yellow Springs Instrument Company, Yellow Springs, OH) that are accurate to 0.005°C. Thermistor resistances are read using the multimeter and also sent over the GPIB for computer processing. A picture of the umbilicus with precision thermistors is provided in Figure 6.

The suit also has six skin thermistors wired into it, one for each region. In addition, there is another thermistor for rectal temperature measurement, two for air space temperature measurements and one for measurement of a common inlet water temperature. These thermistors are standard Yellow Springs Instrument Company, series 700 probes and are read using a separate multimeter (PREMA, model 5001) that also communicates with the system computer over the GPIB. The multimeters are housed at the top of the system rack and are pictured in Figure 7.

Figure 7. Multimeters for signal digitization

Data capture and calculations are carried out using a Personal Computer (Intel Pentium 4 processor running at 1.2 GHz, 1.0 Mb RAM) running software written for this application in LABVIEW™ (National Instruments Corporation, Austin, TX).

In the program, thermistor resistances are converted to temperatures using the Steinhart and Hart equation: $\frac{1}{t} = a + b \times \log(r) + c \times \log(r)^3$

Where: r = resistance in ohms, and a, b, and c are constants provided by the manufacturer's calibration.

Raw flow values are computed as $\dot{v}_w = a \times v^3 + b \times v^2 + c \times v + d$

Where: $\dot{v}_w$ = water flow, v = voltage and a, b, c, and d are constants provided by the

manufacturers calibration.

Flow is converted into mass flow by multiplying the raw flow by the density of water at the inlet temperature. The density is calculated as:

$$D_w = 0.99 + 0.1 \times 1.8313^{(-0.0145 \times T_w)} - 0.1659^{(0.0377 \times T_w)} - 0.6935^{(-0.0631 \times T_w)}$$

Where D_w is the density of water, and T_w is the temperature of the water in °C.

Mass flow is then: $\dot{m}_w = \dot{v}_w \times D_w$

The heat loss, $\dot{Q}$, for each segment is calculated as $\dot{Q} = \dot{m}_w \times (T_{wo} - T_{wi}) \times 69.733333$

Where T_{wo} is the outlet water temperature, T_{wi} is the inlet water temperature, and 69.73333 is the conversion factor for kcal • min^{-1} to watts.

Within the program, the calculations are updated each minute, and a graphical display of the results are updated every 2 minutes. A picture of the computer display during data collection is shown in Figure 8.

Figure 8. A view of the computer display screen

The LCG calorimeter can be used to measure changes in body heat content during a variety of activities, most notably, exercise. When used in conjunction with indirect calorimetry from open-circuit spirometry measures, the system can be used to measure heat storage associated with changes in metabolic output. The calorimeter can also be used, at least theoretically, to measure the cooling capacity provided by immersion of the hands and/or feet in cold water, or contact of the hands and/or feet with cold surfaces. The fact that heat exchange is measured regionally should allow the determination of the regional distribution of the heat loss associated with such local cooling.

At this point, it would appear that one of the possible drawbacks of the LCG calorimeter is that enough cooling power must be provided to keep the individual in the garment from sweating. The "clamping" of the skin temperature may alter the pathways for heat loss during exercise. Any effects of such clamping remain to be determined. Additionally, with suitable garments around the exercising subject, it may be possible to allow the subject to sweat and measure that heat loss indirectly by cooling the sweat through its contact with the suit tubes. Again, work in this area needs to be done.

This LCG calorimeter provides a versatile tool for exploring a range of physiological questions related to heat exchange.